Mountain glaciers: on thinning ice

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Abstract: Mountain glaciers are key indicators of climate change. Glacier changes are the most visible evidence of global climate change we have. They affect the appearance of the landscape in high mountains and impact regional water supplies, local hazard conditions and global sea levels. Glaciers may be found in, and compared across, all latitudes – from the equator to the poles. Due to their sensitivity to climatic changes, glaciers are key indicators for use in global climate observation systems

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3 Mountain Glaciers

Ellesmere Island (J. Noetzli)

Mountain Glaciers: On Thinning Ice

Michael Zemp
Wilfried Haeberli
Martin Hoelzle

Mountain glaciers are key indicators of climate change. Glacier changes are the most visible evidence of global climate change we have. They affect the appearance of the landscape in high mountains and impact regional water supplies, local hazard conditions and global sea levels. Glaciers may be found in, and compared across, all latitudes – from the equator to the poles. Due to their sensitivity to climatic changes, glaciers are key indicators for use in global climate observation systems.

Chopicalqui, Peru (E. Hegglin)

Glaciers have been observed in an internationally coordinated way for more than a century [1, 2]. The results from data collected around the world are not comforting – the outlook for the near future is even less so: evidence of accelerated glacier shrinkage at a global scale is mounting. The decadal average rate of thickness loss measured via 37 reference glaciers worldwide (Figure 3.1) has tripled since the 1980s (Figure 3.2). The record loss documented in the 1980–1999 time period (in 1998) has already been exceeded four times in the twenty-first century: in 2003, 2006, 2010 and 2011 [3]. Aerial and satellite data confirm the trend and point to even higher losses in certain regions such as southern Alaska. At the same time, decadal regional and individual exceptions have been found, showing intermittent glacier re-advance, for example, in the wetter parts of Norway, in New Zealand and in the western Himalayas. But assessed globally according to a centennial time scale, the dominant trend is one of rapid glacier melting.

Global glacier distribution and changes in mass and extent

According to recent global estimates, there are 170 000 glaciers worldwide covering an area of 730 000 km^2 [4]. More than 80 percent of that area is located in the Canadian Arctic, Alaska, High Mountain Asia and around the continental ice sheets of Antarctica and Greenland. If all the world's glaciers were to melt, it would result in a mean sea level rise of roughly half a metre [5, 6]. Much of the water locked in the world's glaciers may indeed reach the global ocean within the next few centuries [7].

Measurements of change in the length of glaciers were the main data collected during the initial phases of international glacier monitoring, which began in 1894. The data from these simple observations are extremely robust. They leave no doubt that mountain glaciers worldwide have been shrinking rapidly since the late twentieth century. Evidence suggests that this strikingly synchronous global retreat is exceptional; in many places, glaciers have now been reduced close to their minimum extent during the warmest periods of the Holocene – i.e. in the past 10 000 years [8] – and some have shrunk even smaller.

Observations based on mass balance – i.e. the difference between accumulation (snowfall) and ablation (melting) – indicate that ice loss is occurring at a considerably higher rate than greenhouse gas effects alone would predict. This means that feedback processes are probably playing an increasing role, in particular the mass balance altitude feedback and decreasing reflectivity (albedo) due to darkening glacier surfaces, retreating snow lines and enhanced dust deposition [9, 10].

New measurement techniques, new insights

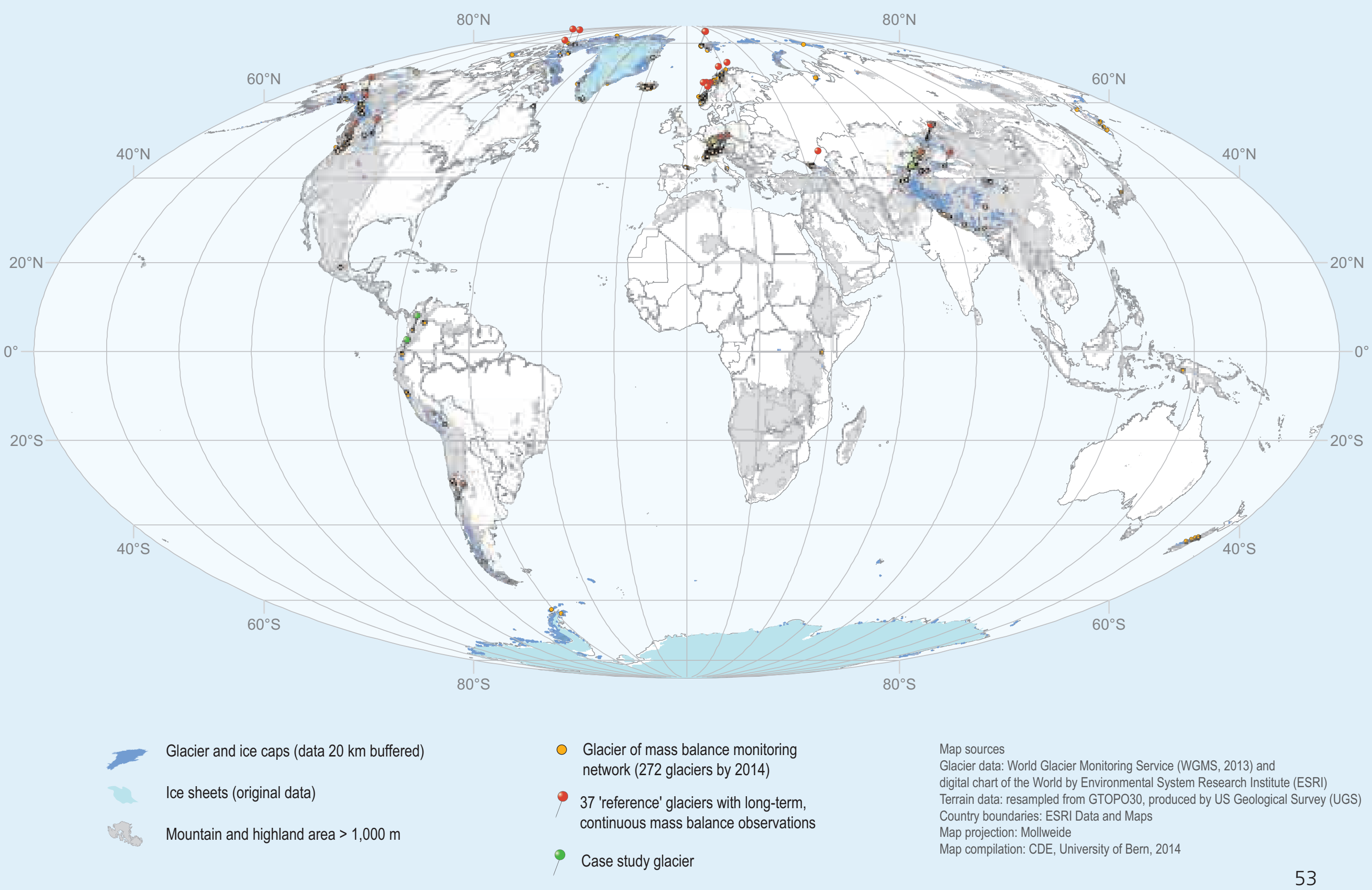
Recently, glacier inventories based on satellite imagery and digital terrain information have enabled new ways of documenting the distribution of glaciers and ice caps and changes affecting them. Computer models that combine data from observed time series with satellite information make it possible to examine changes across larger glacier ensembles, spanning entire mountain regions. The results show clearly that even if global warming is kept to 2 °C, many small- to medium-size glaciers in mountain areas are likely to disappear entirely in the coming decades, with serious consequences for hazard risks and water cycles [11]. Rather than gradually retreating, many large glaciers may develop extreme disequilibria, causing them to down-waste or collapse, as is being observed with increasing frequency.

Techniques have also been developed to model the topography that will be exposed by vanishing glaciers. This helps to anticipate the formation of new lakes in local depressions of glacier beds [12]. Some of these new lakes may bear potential

Policy messages

- Continue and expand the monitoring of glaciers via *in situ* and remotely sensed observations.
- Promote free, unrestricted international sharing of standardized data and information on glacier distribution and changes.
- Promote assessments of glacier change impacts on local hazard risks, on regional freshwater availability and on global sea level rise.

Figure 3.1. Global distribution of glaciers, ice caps and ice sheets as well as the locations of 37 reference glaciers with long-term continuous mass balance observations

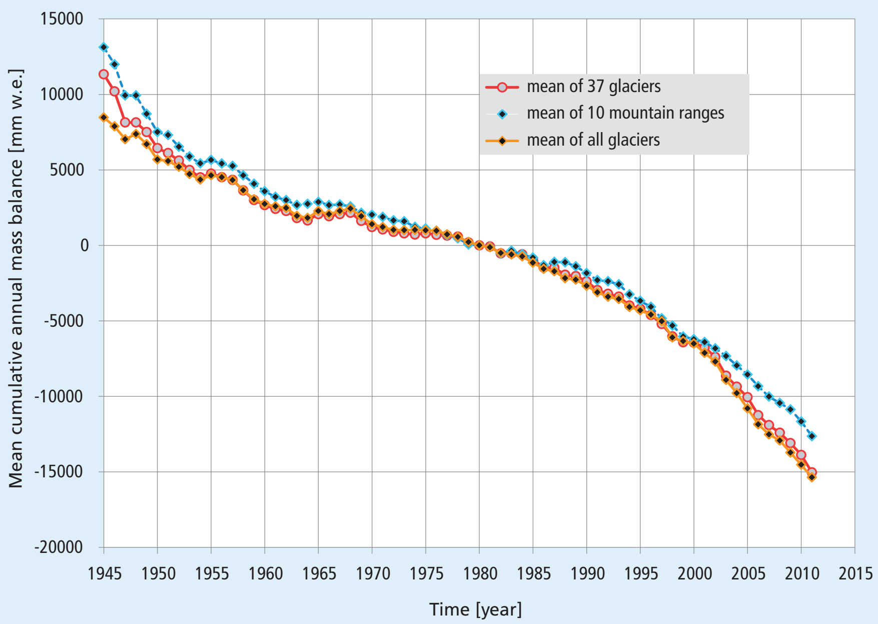


for generating hydropower or for preserving aesthetic appeal when the beauty of a glacier is lost. However, they also present a growing risk of flooding and far-reaching debris flows caused by moraine breaching or rock avalanches from deglaciated slopes or slopes containing degrading permafrost [13].

Impacts of glacier retreat

The most serious impact of melting mountain glaciers concerns regional and global water cycles. Glacier melting will remain a major contributor to sea level rise in this century [11], and the seasonality of runoff will change dramatically in some regions due to the combined effects of diminished snow storage, earlier snowmelt and decreasing glacier melt. To assess the importance of glacier melt to water availability in a given place, one must consider the seasonal glacier contribution to water supplies vis-à-vis the catchment size and corresponding contributions from snowmelt and precipitation. Glaciers' importance to water supplies is minor in monsoonal climates, moderate in most mid-latitude basins and major in seasonally or perennially dry basins such as those in Central Asia or on the western slopes of the tropical Andes [14]. Currently, roughly one billion people – mainly in Asia, North and South America and Central and Southern Europe – depend on snow and glacier meltwater during the dry season and could be seriously affected by any changes [15]. In the future, water scarcity in long droughts exacerbated by changing snow and ice cover in high mountain ranges could seriously impact people's livelihoods and the economy. Problems that could arise during warm or dry seasons include diminished water supplies, longer-lasting discharge minima and low flow periods in rivers, lower lake and groundwater levels, higher water temperatures, disrupted aquatic systems and diminished hydropower generation. These effects could be compounded by increasing demand for water due to growing populations, urbanization, industrialization, irrigation, hydropower generation and firefighting. A combination of decreased supply and increased demand such as this could cause conflicts. Together with higher air temperatures, increased evaporation and changing snow conditions, the disappearance of mountain glaciers could dramatically heighten two fundamental questions: Who owns the water? And who decides how it is used in critical situations?

Figure 3.2. Mean global cumulative mass balance since 1945/1946. Positive and negative values indicate ice gain or loss, respectively, compared with the year 1980. The sample consists of observations from about 250 glaciers in total, with long-term observation series from 37 glaciers in ten mountain ranges. The mean balances of the first years are of limited value due to the very small sample size. w.e.: water equivalent
Source: WGMS (2013)



World Glacier Monitoring Service (WGMS)

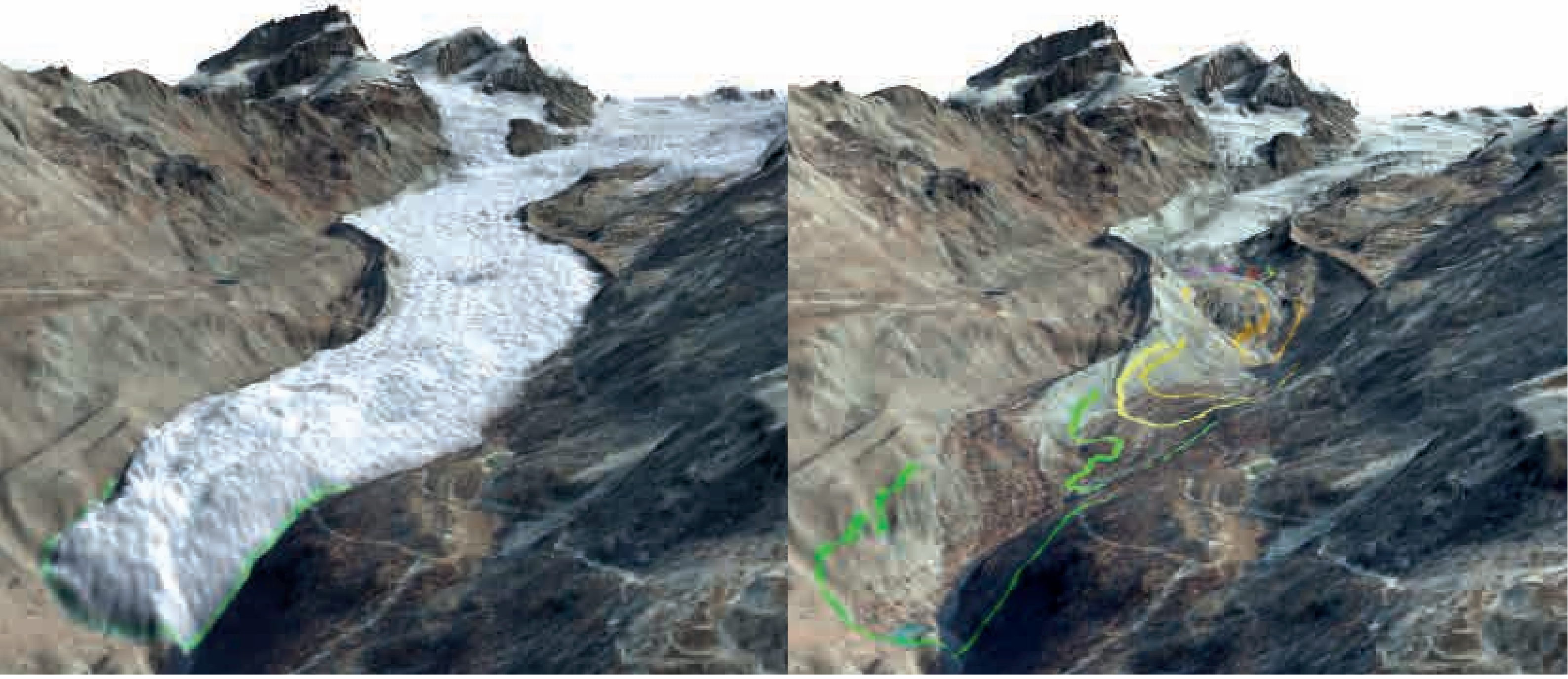
For over a century, the Swiss-led World Glacier Monitoring Service (WGMS) and its predecessor organizations have coordinated the worldwide compilation and free dissemination of glacier observations. Today, together with the US National Snow and Ice Data Center (NSIDC) and the Global Land Ice Measurements from Space (GLIMS) initiative, WGMS supervises the Global Terrestrial Network for Glaciers (GTN-G): the framework for internationally coordinated monitoring of glaciers within the Global Climate Observing System (GCOS), supporting the United Nations Framework Convention on Climate Change (UNFCCC). WGMS is financed by the Federal Office of Meteorology and Climatology MeteoSwiss in the framework of GCOS Switzerland.

This effort relies on a network of scientific collaboration comprising over 1 000 observers working in more than 30 countries. It has resulted in an unprecedented global database on glacier distribution and change. However, the resulting observations – especially from long-term programmes – are strongly biased towards the northern hemisphere and Europe. Regions with limited observational coverage include strongly glaciated areas in the Arctic and Antarctic as well as in the Andes and Asia (see Figure 3.1).

For more information see:

- World Glacier Monitoring Service: http://www.wgms.ch
- Website of the Global Terrestrial Network for Glaciers: http://www.gtn-g.org
- Report on global glacier changes (facts and figures): http://www.grid.unep.ch/glaciers/

Figure 3.3. Views of Findelengletscher, Switzerland, in 1862 (left) and 2010 (right), created based on historical maps and using modern laser scanning, respectively. The figures are provided by P. Rastner, University of Zurich, and were produced within the Glacier Laser Scanning Experiment Oberwallis project supported by the Swiss energy utility Axpo



Capacity Building and Twinning for Climate Observing Systems

Among the regions with limited glacier observations, the Andes and Central Asia are probably the most vulnerable to impacts of climate and glacier changes. In these regions, glaciers significantly contribute to water supplies during dry seasons, and people and infrastructure are especially vulnerable to glacier-related hazards such as glacier lake outburst floods. Both regions are currently the focus of international capacity-building and twinning programmes. But all related efforts to understand secondary climate change impacts and identify mitigation and adaptation measures are hampered by a lack of long-term, high-quality meteorological/glacier observation series. The Capacity Building and Twinning for Climate Observing Systems (CATCOS) project – coordinated by the Federal Office of Meteorology and Climatology MeteoSwiss and funded by the Swiss Agency for Development and Cooperation (SDC) – aims at improving the monitoring of greenhouse gases, aerosols and glacier mass balances in regions of the world where data are lacking. In close collaboration with regional partners, the glaciological work packages of the CATCOS project seek to continue *in situ* mass balance measurement programmes in Colombia and Ecuador in addition to carrying out new geodetic surveys of glaciers; and they seek to resume interrupted *in situ* mass balance measurements in Kyrgyzstan and Uzbekistan.

Note: This chapter is an updated version of W. Haeberli and M. Zemp's contribution to: Mountains and Climate Change (2009), pp. 22–25

Demonstration of snow density measurements during a summer school held in the framework of the CATCOS project in Zermatt, Switzerland (M. Zemp)

Resuming Glacier Monitoring in Kyrgyzstan

The mountain ranges of Central Asia are water towers for large populations. Glacier runoff represents an important freshwater resource in the extensive arid parts of the region. The mass balance of glaciers here is also an important indicator of climate change.

Ryskul Usubaliev
Erlan Azisov

Abramov Glacier, Kyrgyzstan (H. Machguth)

International guidelines for monitoring of mountain glaciers recommend combining *in situ* measurements (mass balance, front variations) with remote sensing (inventories) and numerical modelling. This helps to bridge the gap between detailed (process-oriented) local studies of glaciers and globally relevant datasets.

Certain glaciers in Central Asia – namely, Abramov and Golubin – have been listed as reference glaciers by the World Glacier Monitoring Service (see Box on page 55). They represent important mountain ranges, such as the Pamir-Alay and the Tien Shan mountains. Long-term mass balance series – i.e. series over 20 years old – are available for these glaciers. Following the collapse of the former Soviet Union, measurement efforts were largely abandoned. In late summer 2011, scientists from Kyrgyzstan, Uzbekistan, Switzerland and Germany resumed measurement activities for the Abramov glacier in the Pamir-Alay Mountains. This occurred within the Capacity Building and Twinning for Climate Observing Systems (CATCOS) project (see Box on page 56) and the Central Asian Water project (CAWa). Measurements were also resumed for Golubin Glacier, Suek Zapadniy and Glacier 354 in the Tien Shan Mountains in 2010. The resulting mass balance data were analysed together with snow line observations from terrestrial cameras and compared with measurements made earlier.

Efforts towards capacity building and twinning are intended to transfer leadership of the observation programme to regional partners and to generate information for regional stakeholders involved in water management, disaster risk reduction and the health sector.

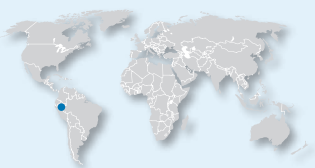
Strengthening Glacier Monitoring in the Tropical Andes

Glaciers in the tropical Andes are known to be especially sensitive to climate change. Due to the specific climate conditions in the tropical zone, ice melt occurs year-round on the lowest part of the glaciers. Thus, glacier termini display a short-term response to changes in mass balance and climate [1].

Bolivar Cáceres
Jorge Luis Ceballos

Antizana ice cap, Ecuador (M. Zemp)

Tropical glaciers reached their "Little Ice Age" maximum extent between the late seventeenth and early nineteenth centuries. Since then these glaciers have exhibited a general retreat, marked by two periods of acceleration: one in the late nineteenth century, and another in the last 30 years – the latter being the more pronounced. These changes are best captured by monthly mass balance measurements performed in Bolivia, Ecuador and Colombia. The main drivers of recent glacier shrinkage are believed to be the increased frequency of El Niño events and changes in their spatial and temporal occurrence in combination with a warming troposphere over the tropics [2]. In the future, increasing air temperatures and minimal change in precipitation could greatly reduce glacial coverage and even eliminate small glaciers whose upper reaches are located close to the current equilibrium-line altitude [2]. This is a serious concern because large populations live in the arid regions to the west of the Andes and depend on water supplies from high-altitude glaciated mountain chains for agricultural, domestic consumption and hydropower [3].



Nevado del Tolima (foreground) and Nevado del Ruiz (background, right) – two active volcanoes – and the inactive Santa Isabel (background, centre), Cordillera Central of Colombia (J. Ramírez Cadena)

The Capacity Building and Twinning for Climate Observing Systems (CATCOS) project (see Box on page 56) aims at strengthening the glacier monitoring programmes in Colombia and Ecuador. It supports the continuation of mass balance measurements at the Antizana ice cap in Ecuador. In a joint effort with regional partners, participants are implementing a new geodetic survey based on aerial photography in order to validate *in situ* observations and assess the ice cap's overall decadal ice volume change. In Colombia, the project supports the continuation of the mass balance programme at Conejeras, an outlet glacier of the Nevado de Santa Isabel. The project further complements this effort with a terrestrial laser-scanning survey of the glacier surface as well as a ground-penetrating radar survey to determine remaining ice thickness. Together with the mass balance programme at Zongo Glacier in Bolivia, the two monthly observation series in Colombia and Ecuador are vital to improving our understanding of climate change in the mid-troposphere of the tropical Andes as well as its impacts on glaciers, runoff and the availability of freshwater for regional populations and ecosystems.

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2 Mountain Waters

Mountain Waters and Climate Change From a Socio-Economic Perspective
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Andean Water for Peru's Coastal Deserts
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Assessing Water Balance in the Upper Indus Basin
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Impacts of Global Warming on Mountain Runoff: Key Messages From the IPCC Report
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Peak Water: An Unsustainable Increase in Water Availability From Melting Glaciers
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3 Mountain Glaciers

Mountain Glaciers: On Thinning Ice
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Resuming Glacier Monitoring in Kyrgyzstan
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4 Mountain Hazards

Mountain Hazards and Climate Change
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Erosion Control and Climate Change in Japan
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Abnormal Monsoon Floods in the Indian Trans-Himalayas
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Reducing Vulnerability to Climatic Risks in the Indian Himalayan Region
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Pokhara's Elusive Past
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5 Mountain Biodiversity

Biodiversity in Mountains: Natural Heritage Under Threat
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Iran: Home to Unique Flora Threatened by Global Warming
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Climate-Resilient Pasture Management in the Ethiopian Highlands
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6 Food Security in Mountains

Mountains, Climate Change and Food Security
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Preserving Agroforestry on Mount Kilimanjaro
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Adapting to Climate Change in the Peruvian Andes
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Promoting Water Use Efficiency in Central Asia
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Food Security in the Hindu Kush Himalayas and the Added Burden of Climate Change
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7 Mountain Economy

Mountain Economies, Sustainable Development and Climate Change
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Alpacas or Llamas? Management of Uncertainty Among Livestock Keepers in the High Andes
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Mountains and Climate Change: A Global Concern

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